5.2 ENERGY IMPACTS

Energy conservation is an important goal for PWB manufacturers, as companies strive to cut costs and seek to improve environmental performance and global competitiveness. Energy use has become an important consideration in the manufacture of PWBs as much of the manufacturing process requires potentially energy-intensive operations, such as the addition of heat to process baths. This is especially true in the operation of the MHC process, where energy is consumed by immersion heaters, fluid pumps, air blowers, agitation devices such as vibrating motors, and by conveyorized transport systems. The focus of this section is to perform a comparative analysis of the relative energy consumption rates of the baseline MHC process and process alternatives and to qualitatively assess their relative energy impacts throughout the product life cycle.

Data collected for this analysis focus on the use of MHC chemical products in PWB manufacturing. Although a quantitative life-cycle analysis is beyond the scope and resources of this project, a qualitative discussion of other life-cycle stages is presented, including a discussion of the energy impacts of manufacturing or synthesizing the chemical ingredients of MHC products, as well as a discussion of the relative life-cycle environmental impacts resulting from energy consumption during the use of MHC chemicals. Section 5.2.1 discusses energy consumption during MHC process operation. Section 5.2.2 discusses the environmental impacts of this energy consumption, while Section 5.2.3 discusses energy consumption of other life-cycle stages. Section 5.2.4 presents conclusions of the comparative energy analysis.

5.2.1 Energy Consumption During MHC Process Operation

To determine the relative rates of energy consumption during the operation of the MHC technologies, specific data were collected regarding energy consumption through the Performance Demonstration project and through dissemination of the Workplace Practices Survey to industry members. Energy data collected include the following:

- Process specifications (i.e., type of process, facility size, etc.).
- Physical process parameters (i.e., number of process baths, bath size, bath conditions such as temperature and mixing, etc.).
- Process automation (i.e., conveyorized, computer-controlled hoist, manual, etc.).
- Equipment description (i.e., heater, pump, motor, etc.).
- Equipment energy specifications (i.e., electric load, duty, nominal power rating, horsepower, etc.).

Each of the MHC process alternatives consist of a series of chemical baths which are typically separated by one or more water rinse steps. In order for the process to perform properly, each chemical bath should be operated within specific supplier recommended parameters, such as parameters for bath temperature and mixing. Maintaining these chemical baths within the desired parameters often requires energy-consuming equipment such as immersion heaters, fluid circulation pumps, and air blowers. In addition, the degree of process automation affects the relative rate of energy consumption. Clearly, conveyorized equipment requires energy to operate the system, but also non-conveyorized systems require additional equipment not found in conveyorized systems, such as panel agitation equipment.

Table 5.4 lists the types of energy-consuming equipment used in MHC process lines and the function of the equipment. In some cases, one piece of equipment may be used to perform a function for the entire process line. For example, panel vibration is typically performed by a single motor used to rock an apparatus that extends over all of the process tanks. The apparatus provides agitation to each individual panel rack that is connected to it, thus requiring only a single motor to provide agitation to every bath on the process line that may require it. In other cases, each process bath or stage may require a separate piece of energy-consuming equipment.

Table 5.4 Energy-Consuming Equipment Used in MHC Process Lines

Type of Equipment	Function
Conveyor Drive Motor	Powers the conveyor system required to transport PWB panels through the MHC process.
Immersion Heater	Raise and maintain temperature of a process bath to the optimal operating temperature.
Fluid Pump	Circulate bath fluid to promote flow of bath chemicals through drilled through-holes and to assist filtering of impurities from bath chemistries.
Air Pump	Compress and blow air into process baths to promote agitation of bath to ensure chemical penetration into drilled through-holes. Also provides compressed air to processes using air knife to remove residual chemicals from PWB panels.
Panel Agitation Motor	Agitate apparatus used to gently rock panel racks back and forth in process baths. Not required for conveyorized processes.
Gas Heater	Heat PWB panels to promote drying of residual moisture remaining on the panel surface.
Ventilation Equipment	Provides ventilation required for MHC bath chemistries and to exhaust chemical fumes.

To assess the energy consumption rate of each of the MHC alternatives, an energy use profile was developed for each MHC technology that identified typical sources of energy consumption during the operation of the MHC process. The number of MHC process stages that result in the consumption of energy during their operation was determined from Performance Demonstration and Workplace Practices Survey data. This information is listed in Table 5.5 according to the function of the energy-consuming equipment. For example, a typical non-conveyorized electroless copper process consists of four heated process baths, two baths requiring fluid circulation, and a single process bath that is air sparged. The panel vibration is typically performed by a single motor used to rock an apparatus that extends over all of the process tanks. Ventilation equipment is not presented in Table 5.5 because the necessary data were not collected during the Performance Demonstration or in the Workplace Practices Survey. However, the amount of ventilation required varies according to the type of chemicals, bath operating conditions, and the configuration of the process line. Because they are enclosed, the ventilation equipment for conveyorized processes are typically more energy efficient than non-conveyorized processes.

Table 5.5 Number of MHC Process Stages that Consume Energy by Function of Equipment

Process Type	Function of Equipment[a]					
	Conveyor	Bath Heat	Fluid Circulation	Air Sparging[b]	Panel Agitation[c]	Panel Drying
Electroless Copper, non-conveyorized (BASELINE)	0	4	2	1	1	0
Electroless Copper, conveyorized	1	5	7	0	0	0
Carbon, conveyorized	1	2	6	0	0	2
Conductive Polymer, conveyorized	1	2	4	0	0	0
Graphite, conveyorized	1	1	4	0	0	1
Non-Formaldehyde Electroless Copper, non-conveyorized	0	5	2	0	1	0
Organic-Palladium, non-conveyorized	0	3	3	0	1	0
Organic-Palladium, conveyorized	1	3	7	0	0	0
Tin-Palladium, non-conveyorized	0	3	3	1	1	0
Tin-Palladium, conveyorized	1	3	9	0	0	0

[a] Table entries for each MHC alternative represent the number of process baths requiring each specific function. All functions are supplied by electric equipment, except for drying, which is performed by gas-fired oven.
[b] Air sparging is used selectively by some manufacturers to enhance bath performance. Sparging may not be required for all product lines or facilities using an alternative.
[c] Processes reporting panel agitation for one or more baths are entered as one in the summary regardless of the number since a single motor can provide agitation for the entire process line.

The electrical energy consumption of MHC line equipment as well as equipment specifications (power rating, average duty, and operating load), were collected during the Performance Demonstration. In cases where electricity consumption data were not available, the electricity consumption rate was calculated using the following equation and equipment specifications:

$$EC = NPR \times OL \times AD \times (1kW/0.746\ HP)$$

where:

EC = electricity consumption rate (kWh/day)
NPR = nominal power rating (HP)
OL = operating load (%), or the percentage of the maximum load or output of the equipment that is being used
AD = average duty (h/day), or the amount of time per day that the equipment is being operated at the operating load

Electricity consumption data for each equipment category were averaged to determine the average amount of electricity consumed per hour of operation for each type of equipment per process. The natural gas consumption rate for a drying oven was supplied by an equipment vendor. Electricity and natural gas consumption rates for MHC equipment per process stage are presented in Table 5.6.

Table 5.6 Energy Consumption Rates for MHC Equipment

Function of Equipment	Type of Equipment	Energy Consumption Rates Per Process Stage	
		Electricity[a] (kW/hr)	Natural Gas[b] (ft^3/hr)
Conveyorized Automation	Conveyor System	14.1	-
Non-Conveyorized Process Line[c]	Panel Agitation Motor	3.1	-
Heat	Immersion Heater	4.8	-
Fluid Circulation	Fluid Pump	0.7	-
Air Sparging	Air Pump	3.5	-
Drying Oven	Gas Heater	-	90

[a] Electricity consumption rates for each type of equipment were calculated by averaging energy consumption data per stage from the performance demonstrations. If required, consumption data were calculated from device specifications and converted to total kW/hr per bath using 1 HP = 0.746 kW.
[b] Natural gas consumption rate for the gas heater was estimated by an equipment vendor (Exair Corp.).
[c] Non-conveyorized process lines are assumed to be manually operated with no automated panel transport system. The electricity consumption rate reported includes the electricity consumed by a panel agitation motor.

The total electricity consumption rate for each MHC alternative was calculated by multiplying the number of process stages that consume electricity (Table 5.5) by the appropriate electricity consumption rate (Table 5.6) for each equipment category, then summing the results. The calculations are described by the following equation:

$$ECR_{total} = \sum_{i=1}^{n} [NPS_i \text{ x } ECR_i]$$

where:

ECR_{total} = total electricity consumption rate (kW/h)
NPS_i = number of process stages requiring equipment i
ECR_i = energy consumption rate for equipment i (kW/h)

Natural gas consumption rates were calculated using a similar method. The individual energy consumption rates for both natural gas and electricity were then converted to British Thermal Units (Btu) per hour and summed for each alternative to give the total energy consumption rate for each MHC alternative. The individual consumption rates for both natural gas and electricity, as well as the hourly energy consumption rate calculated for each of the MHC process alternatives are listed in Table 5.7.

These energy consumption rates only consider the types of equipment listed in Table 5.4, which are commonly recommended by chemical suppliers to successfully operate an MHC process. However, equipment such as ultrasonics, automated chemical feed pumps, vibration units, panel feed systems, or other types of electrically powered equipment may be part of the MHC process line. The use of this equipment may improve the performance of the MHC line, but is not required in a typical process for any of the MHC technologies.

Table 5.7 Hourly Energy Consumption Rates for MHC Alternatives

Process Type	Energy Consumption Rates		Hourly Consumption Rate[a] (Btu/hr)
	Electricity (kW/hr)	Natural Gas (ft^3/hr)	
Electroless Copper, non-conveyorized (BASELINE)	27.2	-	92,830
Electroless Copper, conveyorized	43	-	146,750
Carbon, conveyorized	27.2	180	276,430
Conductive Polymer, conveyorized	26.5	-	90,440
Graphite, conveyorized	21.7	90	165,860
Non-Formaldehyde Electroless Copper, non-conveyorized	28.5	-	97,270
Organic-Palladium, non-conveyorized	19.6	-	66,890
Organic-Palladium, conveyorized	33.4	-	113,990
Tin-Palladium, non-conveyorized	23.1	-	78,840
Tin-Palladium, conveyorized	34.8	-	118,770

[a] Electrical energy was converted at the rate of 3,413 Btu per kilowatt hour where a kWh = 1 kW/hr. Natural gas consumption was converted at the rate of 1,020 Btu per cubic feet of gas consumed.

To determine the overall amount of energy consumed by each technology, the hourly energy consumption rate from Table 5.7 was multiplied by the amount of time needed for each alternative to manufacture 350,000 ssf of board (the average MHC throughput of respondents to the Workplace Practices Survey). Because insufficient survey data exist to accurately estimate the amount of time required for each process to produce the 350,000 ssf of board, the operating time was simulated using a computer model developed for each alternative. The results of the simulation along with a discussion of the data and parameters used to define each alternative are presented in Section 4.2, Cost Analysis. The hours of MHC operation required to produce 350,000 ssf of board from the simulation, the total amount of energy consumed, and the energy consumption rate for each alternative per ssf of board produced are presented in Table 5.8.

Table 5.8 shows that all of the alternatives are more energy efficient than the traditional non-conveyorized electroless copper process. This is primarily attributable to a process operating time for non-conveyorized electroless copper that is two to eight times greater than the operating times of the alternatives. Other processes with high energy consumption rates include non-formaldehyde electroless copper due to its long operating time and both carbon and graphite due to their high hourly consumption rates. The three processes consuming the least energy per unit of production are the organic-palladium non-conveyorized system and the conductive polymer and tin-palladium conveyorized systems.

The performance of specific MHC processes with respect to energy is primarily dependent on the hourly energy consumption rate (Table 5.7) and the overall operating time for the process (Table 5.8). Non-conveyorized processes typically have lower hourly consumption rates than conveyorized processes because the operation of conveyorized equipment is more energy-intensive. Although conveyorized processes typically have higher hourly consumption rates, these differences are more than offset by the shorter operating times that are required to produce an equivalent quantity of PWBs.

Table 5.8 Energy Consumption Rate per ssf of Board Produced for MHC Alternatives

Process Type	Process Operating Time[a] (hours)	Total Energy Consumed (Btu/350,000 ssf)	Energy Consumption Rate (Btu/ssf)
Electroless Copper, non-conveyorized (BASELINE)	2,160	2.01×10^8	573
Electroless Copper, conveyorized	329	4.83×10^7	138
Carbon, conveyorized	650	1.80×10^8	514
Conductive Polymer, conveyorized	367	3.31×10^7	94.7
Graphite, conveyorized	450	7.46×10^7	213
Non-Formaldehyde Electroless Copper, non-conveyorized	971	9.44×10^7	270
Organic-Palladium, non-conveyorized	350	2.34×10^7	66.9
Organic-Palladium, conveyorized	456	5.19×10^7	148
Tin-Palladium, non-conveyorized	581	4.58×10^7	131
Tin-Palladium, conveyorized	284	3.38×10^7	96.4

[a] Times listed represent the operating time required to manufacture 350,000 ssf of board by each process as simulated by computer model.

When MHC processes with both non-conveyorized and conveyorized versions are compared, the conveyorized versions of the alternatives are typically more energy efficient. Table 5.8 shows this to be true for both the electroless copper and tin-palladium processes. The organic-palladium processes are the exceptions. The non-conveyorized configuration of this process not only has a better hourly consumption rate than the conveyorized, but also benefits from a faster operating time, a condition due to the low number of process baths and its short rate-limiting step.[1] These factors combine to give the non-conveyorized organic-palladium process a lower energy consumption rate than the conveyorized version and make it the most energy efficient process evaluated.

Finally, it should be noted that the overall energy use experienced by a facility will depend greatly upon the operating practices and the energy conservation measures adopted by that facility. To minimize energy use, several simple energy conservation opportunities are available and should be implemented. These include insulating heated process baths, using thermostats on heaters, and turning off equipment when not in use.

5.2.2 Energy Consumption Environmental Impacts

The production of energy results in the release of pollution into the environment, including pollutants such as carbon dioxide (CO_2), sulfur oxides (SO_x), carbon monoxide (CO), sulfuric acid (H_2SO_4), and particulate matter. The type and quantity of pollution depends on the method of energy production. Typical energy production facilities in the U.S. include hydroelectric, nuclear, and coal-fired generating plants.

[1] The rate-limiting step is the process step that requires more time than the other steps, thus limiting the feed rate for the system.

The environmental impacts attributable to energy production resulting from the differences in energy consumption among MHC alternatives were evaluated using a computer program developed by EPA National Risk Management Research Laboratory called *P2P- version 1.50214* (EPA, 1994). This program can, among other things, estimate the type and quantity of pollutant releases resulting from the production of energy as long as the differences in energy consumption and the source of the energy used (i.e., does the energy come from a coal-fired generating plant, or is it thermal energy from a oil-fired boiler, etc.) are known. The program uses data reflecting the "national average" pollution releases per kilowatt-hour derived from particular sources. Electrical power derived from the average national power grid was selected as the source of electrical energy, while natural gas was used as the source of thermal energy for this evaluation. Energy consumption rates from Table 5.7 were multiplied by the operating time required to produce 350,000 ssf of board reported for each alternative in Table 5.8. These totals were then divided by 350,000 to get the electrical and thermal energy consumed per ssf of board, which were then used as the basis for the analysis. Results of the environmental impact analysis from energy production have been summarized and are presented in Table 5.9. Appendix H contains printouts from the P2P program for each alternative.

Although the pollutant releases reported in Table 5.9 are combined for all media (i.e. air, water, and land), they often occur in one or more media where they may present different hazards to human health or the environment. To allow a comparison of the relative effects of any pollution that may occur, it is necessary to identify the media of releases. Table 5.10 displays the pollutants released during the production of energy, the media into which they are released, and the environmental and human health concerns associated with each pollutant.

The information presented in Tables 5.9 and 5.10 show that the generation of energy is not without environmental consequences. Pollutants released to air, water, and soil resulting from energy generation can pose direct threats to both human health and the environment. As such the consumption of energy by the MHC process contributes directly to the type and magnitude of these pollutant releases. Primary pollutants released from the production of electricity include carbon dioxide, solid wastes, sulfur oxides and nitrogen oxides. These pollutants contribute to a wide range of environmental and human health concerns. Natural gas consumption results primarily in releases of carbon dioxide and hydrocarbons which typically contribute to environmental problems such as global warming and smog. Because all of the MHC alternatives consume less energy than the traditional non-conveyorized electroless copper process, they all decrease the quantity of pollutants released into the environment resulting from the generation of the energy consumed during the MHC process.

Table 5.9 Pollution Resulting From the Generation of Energy Consumed by MHC Technologies

MHC Alternative	Types of Pollutants Released (g/ssf)[a]								
	Carbon Dioxide (CO_2)	Carbon Monoxide (CO)	Dissolved Solids	Hydrocarbons	Nitrogen Oxides (NO_x)	Particulates	Solid Wastes	Sulfur Oxides (SO_x)	Sulfuric Acid (H_2SO_4)
Electroless Copper, non-conveyorized (BASELINE)	120	0.160	0.022	0.140	0.510	0.190	14.0	1.00	0.086
Electroless Copper, conveyorized	28	0.040	0.005	0.034	0.120	0.047	3.4	0.25	0.021
Carbon, conveyorized	56	0.059	0.008	0.260	0.180	0.060	4.3	0.32	0.026
Conductive Polymer, conveyorized	19	0.027	0.004	0.024	0.084	0.032	2.3	0.17	0.014
Graphite, conveyorized	27	0.031	0.004	0.098	0.094	0.033	2.4	0.18	0.014
Non-Formaldehyde Electroless Copper, non-conveyorized	55	0.078	0.010	0.067	0.240	0.092	6.7	0.48	0.041
Organic-Palladium, non-conveyorized	14	0.019	0.003	0.017	0.060	0.023	1.7	0.12	0.010
Organic-Palladium, conveyorized	30	0.043	0.006	0.037	0.130	0.051	3.7	0.27	0.022
Tin-Palladium, non-conveyorized	27	0.038	0.005	0.033	0.120	0.045	3.2	0.23	0.020
Tin-Palladium, conveyorized	20	0.028	0.004	0.024	0.086	0.033	2.4	0.17	0.015

[a] Pollutant totals calculated using the computer program *P2P version 1.50214* developed by EPA's National Risk Management Research Laboratory.

Table 5.10 Pollutant Environmental and Human Health Concerns

Pollutant	Medium of Release	Environmental and Human Health Concerns
Carbon Dioxide (CO_2)	Air	Global warming
Carbon Monoxide (CO)	Air	Toxic organic,[a] smog
Dissolved Solids	Water	Dissolved solids[b]
Hydrocarbons	Air	Odorant, smog
Nitrogen Oxides (NO_x)	Air	Toxic inorganic,[a] acid rain, corrosive, global warming, smog
Particulates	Air	Particulates[c]
Solid Wastes	Soil	Land disposal capacity
Sulfur Oxides (SO_x)	Air	Toxic inorganic,[a] acid rain, corrosive
Sulfuric Acid (H_2SO_4)	Water	Corrosive, dissolved solids[b]

[a] Toxic organic and inorganic pollutants can result in adverse health effects in humans and wildlife.
[b] Dissolved solids are a measure of water purity and can negatively affect aquatic life as well as the future use of the water (e.g., salinity can affect the water's effectiveness at crop irrigation).
[c] Particulate releases can promote respiratory illness in humans.

5.2.3 Energy Consumption in Other Life-Cycle Stages

When performing a comparative evaluation among MHC technologies, the energy consumed throughout the entire life cycle of the chemical products in the technology should be considered. The product use phase is only one aspect of the environmental performance of a product. A life-cycle analysis considers all stages of the life of a product, beginning with the extraction of raw materials from the environment, and continuing on through the manufacture, transportation, use, recycle, and ultimate disposal of the product.

Each stage within this life cycle consumes energy. It is possible for a product to be energy efficient during the use phase of the life cycle, yet require large amounts of energy to manufacture or dispose of the product. The manufacture of graphite is an example of an energy-intensive manufacturing process. Graphite is manufactured by firing carbon black particles to temperatures over 3000 ^{o}F for several hours, which is required to give a crystalline structure to the otherwise amorphic carbon black particles (Thorn, 1996). There are also energy consumption differences in the transportation of wastes generated by an MHC line. The transportation of large quantities of sludge resulting from the treatment of processes with chelated waste streams (i.e., electroless copper) will consume more energy than the transportation of smaller quantities of sludge resulting from processes that do not use chelators. These examples show that energy use from other life-cycle stages can be significant and should be considered when evaluating the energy performance of a product. However, a comprehensive assessment of other life-cycle stages was beyond the scope of this study.

5.2.4 Conclusions

A comparative analysis of the relative energy consumption rates was performed for the MHC technologies. An hourly energy consumption rate was developed for the baseline and each alternative using data collected from industry through a survey. A computer simulation was used to determine the operating time required to produce 350,000 ssf of PWB and an energy consumption rate per ssf of PWB was calculated. The energy consumption rates ranged from 66.9 Btu/ssf for the non-conveyorized organic-palladium process to 573 Btu/ssf for the non-conveyorized electroless copper process. The results indicate all of the MHC alternatives are more energy efficient than the traditional non-conveyorized electroless copper process. It was also found that for alternatives with both types of automation, the conveyorized version of the process is typically the more energy efficient, with the notable exception of the organic-palladium process.

An analysis of the impacts directly resulting from the production of energy consumed by the MHC process showed that the generation of the required energy is not without environmental consequence. Pollutants released to air, water, and soil can result in damage to both human health and the environment. The consumption of natural gas tends to result in releases to the air which contribute to odor, smog and global warming, while the generation of electricity can result in pollutant releases to all media with a wide range of possible affects. Since all of the MHC alternatives consume less energy than electroless copper, they all result in less pollutant releases to the environment from energy production.

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